British Heart Journal, 1974, 36, 822–834.

Acute myocardial infarction
V: Left and right ventricular haemodynamics in cardiogenic shock[1]

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The poor prognosis of patients in acute myocardial infarction and cardiogenic shock can be improved by mechanical assistance to the heart and by emergency coronary surgery. In this group of patients quantitative assessment of myocardial function is necessary for the early recognition of their prognosis. In 42 patients left and right ventricular haemodynamics have been studied in the early phase of infarction. Three main results can be presented.

1) *Left ventricular function is greatly reduced in cardiogenic shock, which is characterized by a low cardiac index, stroke volume, left ventricular stroke work, and a raised left ventricular filling pressure, compared to non-shock patients. Left ventricular contractility as estimated from the relation of mean systolic ejection rate to left ventricular end-diastolic pressure is diminished immediately after myocardial infarction and improves in the next 2 days.*
2) *As a consequence of the site of the necrosis in the left ventricle haemodynamic alterations of the right ventricle follow secondarily the insufficiency of the left chamber, with increasing pressures in the pulmonary circulation and accordingly increasing right ventricular pressure and stroke work. Localization of infarction had no significant effect on the development of right heart failure.*
3) *To estimate the prognosis of seriously ill patients with myocardial infarction haemodynamic assessment is necessary. A single parameter has not been proved to be sufficient. Patients with a left ventricular end-diastolic pressure exceeding 17 mmHg in the presence of a cardiac index below 1·8 l./min/m^2 had a mortality of about 70 per cent. When left ventricular stroke work index/left ventricular end-diastolic pressure declined below 1·2 g m/m^2 mmHg, 80 per cent had an immediate poor prognosis. Using a new shock index, survivors could be separated from non-survivors at the level of 0·3 with a probability of 78 per cent.*

With the introduction of coronary care units, the mortality rate of patients with acute myocardial infarction has been substantially improved (MacMillan *et al.*, 1967; Restieaux *et al.*, 1967). This is mainly due to continuous monitoring, resuscitation techniques with electrical defibrillation and stimulation of the heart, and improved management of cardiac arrhythmias (Lown, Amarashingham, and Neuman, 1962; Mounsey, 1967; Fluck *et al.*, 1967). The outstanding problem in coronary care units today is cardiogenic shock which occurs in 15 to 20 per cent of all patients with acute myocardial infarction reaching the units. Though a variety of drugs have been hopefully used in the treatment of cardiogenic shock, the mortality rate of 85 to 100 per cent has remained unchanged during the past 20 years (Swan *et al.*, 1970a). This is mainly due to three factors:

1) The majority of cases dying with cardiogenic shock have been shown in postmortem studies to have at least 40 per cent of the left ventricular muscle involved; it is most unlikely that drug treatment alone can alter the poor prognosis in these cases (Page *et al.*, 1971).

2) There are some patients, in whom optimally adjusted conservative treatment, in the early phase of cardiogenic shock, may be helpful. But since it is difficult to estimate the functional state of the myocardium from clinical signs, it is likely that optimal

Received 6 August 1973.

[1] With support of the Deutsche Forschungsgemeinschaft SFB 109.

treatment will be applied only in a small percentage of the cases, and that the outcome, therefore, will often be fatal in these.

3) Assist devices (Corday *et al.*, 1970) and surgical methods (Mundth *et al.*, 1970; Buckley *et al.*, 1971) are now available, and may be effective in the treatment of cardiogenic shock. However, even if these new measures had been available in the past, it would have been extremely difficult to decide in time, from clinical signs alone, when to apply these techniques.

Recently, however, haemodynamic monitoring of patients with myocardial infarction has become simpler. This is mainly due to flow-directed micro- and balloon-catheter (Ganz *et al.*, 1970; Hanrath *et al.*, 1972) automatic analysis of cardiac output, and the development of techniques with which catheters can be introduced into the left ventricle even in patients lying in bed and without *x*-ray control (Cohn, Khatri, and Hamosh, 1970; Bleifeld, Merx, and Effert, 1971).

It is the purpose of this report to indicate findings defined by haemodynamic study of 42 patients with acute myocardial infarction, by which bad risk patients can be distinguished reliably from patients with a good prognosis. In this way the indications for mechanical circulatory assist devices and coronary artery surgery can be established in the very early phase of acute myocardial infarction.

Definitions

1) Acute myocardial infarction

This diagnosis was made from a history of long-lasting praecordial pain, the typical signs in the electrocardiogram (World Health Organization, 1959), and an increase in creatine-phosphokinase over 50 mU/ml, in the serum aspartate aminotransferase over 15 mU/ml, and in the lactic dehydrogenase over 200 mU/ml.

2) Cardiogenic shock

The diagnosis of cardiogenic shock was made according to clinical criteria when: a) systolic blood pressure measured by cuff was 90 mmHg or less, for at least 30 minutes, or in patients with hypertension 30 mmHg lower than the systolic blood pressure taken to be normal for these patients; and when, in addition, b) peripheral vasoconstriction, such as a pale and cyanotic skin, c) impairment of cerebral function, e.g. motor restlessness, d) oliguria, with less than 30 ml urine secretion per hour, or anuria, were apparent and, e) tachycardia, which, however, was not accepted as obligatory for the following reasons: sinus tachycardia is often not detected because of disturbances in impulse production and conduction; in the late phase of cardiogenic shock, particularly, a sudden change from tachycardia to bradycardia is sometimes seen (Bleifeld and Merx, 1970).

Cardiovascular shock initiated by cardiac arrhythmias, haemorrhage, pharmacological treatment, or rupture of the heart muscle with tamponade of the heart was excluded.

3) Arterial hypotension

This is characterized by a systolic blood pressure of 90 mmHg or less in the presence of normal perfusion in the periphery, no impairment of urine secretion, and a normal or raised stroke volume (Thomas, Malmcrona, and Shillingford, 1966; Schröder *et al.*, 1968). Cases with such uncomplicated arterial hypotension were not included in this study.

Subjects and methods

From November 1970 to March 1973, 42 patients were studied out of 170 with acute myocardial infarction in the coronary care unit. There were 32 men and 10 women aged between 31 and 84. All patients were suffering from myocardial infarction as defined above. The first haemodynamic measurements were performed immediately after admission to hospital or at least within the first 24 hours. The mean delay time was 5·3 hours. In accordance with the Declaration of Helsinki (1967), the patients and their family were informed of the risks of the study and their permission was obtained. In 2 patients with cardiogenic shock informed consent was obtained from the family only. Necessary treatment was carried out in every case; this included treatment with vasopressors in cardiogenic shock. In cases where heparin had already been given it was discontinued for 10 hours (5 hours before and 5 hours after the haemodynamic measurements).

The haemodynamic measurements were performed under local anaesthesia and without *x*-ray control. The patients remained lying in their beds (Bleifeld *et al.*, 1972). The pressures in the right heart and in the pulmonary artery were obtained with double- or triple-lumen Swan-Ganz balloon catheters (Swan *et al.*, 1970b; Forrester *et al.*, 1972). The catheters were introduced using the Seldinger technique or using a venous cut-down. Red Oedman catheters with end openings and curved tips (Bleifeld *et al.*, 1972) were introduced by the Seldinger technique from the femoral artery into the ascending aorta and left ventricle. The entry of the catheter into the left ventricle was recognized by the typical pressure curves. Ventricular ectopic beats, which were often seen at the moment of entry of the catheter into the left ventricle, disappeared when the catheter was retracted slightly. Pressures were obtained using Statham PE 23 db transducers.[1] Cardiac output was estimated by means of a Waters I 350 cuvette[2] after injection of 1 mg indocyanine green into the pulmonary artery and evaluation of the dilution curves from blood withdrawn from the aorta.

The haemodynamic measurements were repeated during a period not exceeding 5 days. During this time, the

[1] Statham Instruments, Inc., Los Angeles, California 90064, U.S.A.

[2] Waters Instruments, Inc. Rochester, Minnesota, 55901, U.S.A.

catheters remained in the vascular system. After initial registration of the pressure in the left ventricle the arterial catheter was retracted into the aortic arch; for the next measurement it was reintroduced into the ventricle. All catheters were covered and sterile at the insertion site. The catheter entrance was carefully checked daily for the appearance of inflammation. Clotting of the catheters was avoided by filling the venous catheters with heparin and ensuring a continuous flow through the arterial catheters of 40,000 units heparin per day.

Dangerous cardiac arrhythmias, especially ventricular tachycardia or ventricular fibrillation, were not observed. In some cases, especially when the venous catheter was introduced from the arm, bland thrombophlebitis was seen, which, however, could generally be controlled after removal of the catheter. With the exception of one patient, in whom prolonged bleeding after removal of the arterial catheter occurred, no haemorrhagic complications were seen.

Calculations

The cardiac output was calculated from dye dilution curves using the formula of Williams, O'Donovan, and Wood (1966). The mean systolic arterial blood pressure (MSP) was calculated by planimetry. The systemic vascular resistance (SVR) and the pulmonary vascular resistance (PVR) were calculated from the following formulae.

$$SVR = \frac{(MAP - RAP) \cdot 1332}{CO} \text{ (dyn. sec. cm}^{-5})$$

$$PVR = \frac{(MPAP - MPCP) \cdot 1332}{CO} \text{ (dyn. sec. cm}^{-5})$$

where MAP = mean arterial pressure; MPAP = mean pulmonary artery pressure; RAP = right atrial pressure; MPCP = mean pulmonary capillary pressure; CO = cardiac output.

Calculation of the tension time index (TTI) was as follows. $TTI = MSP \times ET \times HR$ (mmHg sec per min) where MSP = mean systolic aortic pressure; ET = ejection time; HR = heart rate.

The stroke work index of the left ventricle (LVSWI) was calculated as follows.

$$LVSWI = (MSP - LVEDP) \cdot \frac{SVI \cdot 1 \cdot 36}{100} \text{ (g m per m}^2\text{b.s.a.)}$$

where LVEDP = end-diastolic pressure in the left ventricle; SVI = stroke volume index; m^2b.s.a. = body surface area in square metres.

A similar formula was used for calculation of the stroke work index of the right ventricle (RVSWI):

$$= (MPAP - RVEDP) \cdot \frac{SVI \cdot 1 \cdot 36}{100} \text{ (g m per m}^2\text{b.s.a.)}$$

where RVEDP = end-diastolic pressure in the right ventricle.

Cardiac minute work (CMW) was calculated by the formula:

$$\frac{(SAP - LVEDP) \cdot CI \cdot 1 \cdot 36}{100} \text{ (g m/min per m}^2\text{b.s.a.)}$$

where SAP = systolic arterial pressure and CI = cardiac index.

Mean systolic ejection rate (MSER) was computed using the formula:

$$MSER = \frac{SVI \cdot 100}{LVET} \left(\frac{\text{ml}}{\text{sec m}^2\text{b.s.a.}}\right).$$

In 35 patients a new prognostic index was examined:

$$\frac{(LVSP - LVEDP) \cdot CI}{LVEDP \cdot AVDO_2}$$

where LVSP = left ventricular systolic pressure; CI = cardiac index; $AVDO_2$ = arteriovenous oxygen difference.

Left (LVER) and right ventricular (RVER) ejection resistance were derived as follows:

$$LVER = \frac{MSP \cdot ET}{SV} \left(\frac{\text{mmHg sec}}{\text{ml}}\right)$$

$$RVER = \frac{MPAP \cdot ET}{SV} \left(\frac{\text{mmHg sec}}{\text{ml}}\right)$$

Statistical analysis was performed by use of the Wilcoxon test, significance of the prognostic index was determined by means of the Kruskal-Wallis-variance analysis.

Results

1) Initial phase (first to the third day) of acute myocardial infarction without shock

Table 1 shows the changes in haemodynamic parameters in patients without cardiac shock. It is apparent that most changes in the haemodynamic function of the left and right ventricle are most prominent in the early stage of myocardial infarction. Only slight changes occur during the following days. The mean arterial blood pressure remained within normal limits. Cardiac output was always reduced to between 4·0 and 4·2 l. Stroke work index of the left ventricle, which was on the first day slightly lower than normal ($44 \cdot 4 \pm 4$ g m/m^2), showed another slight decrease on the second day and returned to almost normal ($48 \cdot 6 \pm 5$ g m/m^2) on the third day. Systemic vascular resistance of $1718 \pm 206 \cdot 6$ dyn sec cm^{-5}, shortly after infarction, was increased compared to normal persons and decreased until the third day to 1613 ± 206 dyn sec cm^{-5} (NS).

The filling pressure of the left ventricle was increased in all cases. The highest values were obtained on the first day with a mean value of $17 \pm 1 \cdot 5$ mmHg. Until the third day, left ventricular filling pressure returned to almost normal values with a mean of $14 \pm 1 \cdot 1$ mmHg. According to the increased left ventricular end-diastolic pressure, the mean pressure in the pulmonary artery was increased during the first three days. The pulmonary vascular resistance, which was initially slightly reduced to 131 ± 30 dyn sec cm^{-5}, increased in the

TABLE I *Haemodynamic data in acute myocardial infarction without cardiogenic shock in the first three days*

	No. of patients	*First day*	*No. of patients*	*Second day*	*No. of patients*	*Third day*	*P<*
Pulmonary circulation							
Right ventricular end-diastolic pressure (mmHg)	23	7·7 ± 0·9	11	8·3 ± 1·7	11	7·8 ± 1·2	NS
Mean pulmonary artery pressure (mmHg)	27	23·0 ± 1·5	21	21·6 ± 1·5	15	20·5 ± 1·2	NS
Pulmonary vascular resistance (dyn sec cm^{-5})	22	31·0 ± 30·9	13	154 ± 45	8	154 ± 47	NS
Right ventricular stroke work index (g m/m^2)	14	11·35 ± 1·38	5	6·85 ± 1·10	6	8·01 ± 1·17	0·01
Right ventricular ejection resistance (mmHg sec per ml)	12	0·09 ± 0·01	6	0·10 ± 0·02	8	0·10 ± 0·01	NS
Systemic circulation							
Left ventricular end-diastolic pressure (mmHg)	27	17·0 ± 1·4	22	15·5 ± 1·2	15	14·0 ± 1·1	NS
Mean arterial pressure (mmHg)	27	94·9 ± 3·5	21	94·1 ± 3·3	15	96·7 ± 4·6	NS
Systemic vascular resistance (dyn sec cm^{-5})	23	1718 ± 206·6	16	1885 ± 127·3	9	1613·0 ± 206	NS
Left ventricular stroke work index (g/m/m^2)	18	43·2 ± 3·8	19	40·2 ± 4·6	13	43·3 ± 5·4	NS
Left ventricular ejection resistance (mmHg sec per ml)	14	0·46 ± 0·05	8	0·47 ± 0·04	6	0·39 ± 0·03	NS
Arteriovenous oxygen difference (% saturation)	21	29·9 ± 1·79	15	34·2 ± 1·44	12	33·1 ± 1·77	NS
Cardiac output (l./min)	24	4·2 ± 0·2	19	4·0 ± 0·2	13	4·2 ± 0·3	NS
Cardiac minute work (kg/m/min per m^2)	15	3·58 ± 0·31	9	3·30 ± 0·23	6	3·95 ± 0·44	NS
Tension time index (mmHg sec per min)	10	2535·9 ± 235·3	2	2359 ± 520	3	1922·7 ± 198·4	NS
Mean systolic ejection rate (ml/sec m^2)	15	11,538 ± 952·8	7	11,047 ± 888·7	6	11,105·3 ± 767·7	NS

following two days to normal values of 154 ± 47 dyn sec cm^{-5}. Right ventricular end-diastolic pressure was only slightly higher than normal in the initial phase and did not change significantly during the next days.

In contrast to the left ventricle, right ventricular stroke work in acute myocardial infarction without shock was found to be increased. On the second day, however, there was a significant reduction in right ventricular stroke work ($P < 0·01$). Apparently after the decrease in mean systolic left ventricular pressure, tension time index continuously decreased during the first three days, but the changes were not significant. The outflow resistance of the left and right ventricle were both increased to 0·46 ± 0·05 and 0·09 ± 0·01 mmHg sec/ml, respectively. The increase of outflow resistance of the left ventricle was mainly a reflection of the decline in stroke volume, whereas the increase in the right ventricle followed the increase in pulmonary artery pressure. Mean systolic ejection rate as well as the ratio between the mean and the left ventricular end-diastolic pressure were constantly diminished during the acute phase.

2) Cardiogenic shock

The extreme reduction of haemodynamic function in the left ventricle in cardiogenic shock is shown in Table 2. All patients with cardiogenic shock died. The filling pressure of the left ventricle was increased to 24 ± 2 mmHg compared with 17 ± 1 mmHg in cases without shock ($P < 0.02$). In 5 of the 7 patients with shock, the left ventricular end-diastolic pressure exceeded 22 mmHg. In comparison, only 8 patients out of 35 without cardiogenic shock had a left ventricular filling pressure over 22 mmHg. Because of a pronounced peripheral vasoconstriction with a mean systemic vascular resistance of 2360 ± 390 dyn sec cm^{-5}, the mean systolic pressure in the left ventricle was 119 ± 8 mmHg in cardiogenic shock, i.e. only slightly reduced when compared with the non-shock cases. In addition, emergency treatment with vasopressor drugs might be responsible for the normal arterial pressure. In the presence of a slightly accelerated heart rate, cardiac output was much reduced to 2.6 ± 0.3 l./min as compared with the other patients (4.2 ± 0.2 l./min) ($P < 0.001$). There were only two patients in the group with cardiogenic shock who had cardiac outputs of more than 3 l./min. Because of the extremely reduced stroke volume, the stroke work index of the left ventricle 19 ± 2.5 g m/m^3 was diminished to less than half that of the patients without cardiogenic shock (46 ± 3.5 g m/m^2) ($P < 0.01$). Similarly, a very low cardiac minute work (1.79 ± 0.2 kg m/min m^2) in cardiogenic shock was found, when compared with 3.6 ± 0.2 kg m/min m^2 in cases without shock ($P < 0.001$). The mean systolic ejection rate in cardiogenic shock was reduced to nearly 65 per cent (6545 ± 520 ml/sec m^2) of the value in cases without shock (10870 ± 583 ml/sec m^2) ($P < 0.001$). These alterations mainly reflect the pronounced reduction in the stroke volume and the prolongation of the ejection time with increasing deterioration of left ventricular function. The outflow impedance to the left ventricle (LVER) was, in shock, significantly increased (0.76 ± 0.05 mmHg sec/ml) as compared to non-shock cases (0.49 ± 0.03 mmHg sec/ml) ($P < 0.01$). This result is in good

TABLE 2 *Haemodynamic data in cardiogenic shock after myocardial infarction compared to the non-schock state*

	Normal	*No. of patients*	*Infarction without shock*	*No. of patients*	*Cardiogenic shock*	*P<*
Pulmonary circulation						
Right ventricular end-diastolic pressure (mmHg)	5	27	7.4 ± 0.7	5	11.4 ± 0.9	0.05
Mean pulmonary artery pressure (mmHg)	16	27	22.9 ± 1.5	6	30.7 ± 2.4	0.02
Pulmonary vascular resistance (dyn sec cm^{-5})	150	22	177.09 ± 17.06	4	183.75 ± 90.08	NS
Right ventricular stroke work index (g m/m^2)	8	27	7.30 ± 1.00	3	11.22 ± 0.83	0.1
Right ventricular ejection resistance (mmHg sec/ml)	0.07	34	0.130 ± 0.01	4	0.218 ± 0.03	0.05
Systemic circulation						
Left ventricular end-diastolic pressure (mmHg)	12	33	17.00 ± 1.45	7	24.1 ± 1.7	0.02
Mean arterial pressure (mmHg)	100	27	94.88 ± 3.47	7	89.9 ± 8.6	NS
Systemic vascular resistance (dyn sec cm^{-5})	1500	23	1811 ± 145	5	2363 ± 393	NS
Left ventricular stroke work index (g m/m^2)	60	33	46.28 ± 3.48	6	19.06 ± 2.53	0.01
Left ventricular ejection resistance (mmHg sec/ml)	0.4	30	0.49 ± 0.03	5	0.760 ± 0.05	0.01
Arteriovenous oxygen difference (% saturation)	24	28	2917 ± 1.3	6	41.3 ± 2.5	0.01
Cardiac output (l./min)	4.5	35	4.2 ± 0.2	6	2.6 ± 0.3	0.01
Cardiac minute work (kg m/min per m^2)	4.5	33	3.55 ± 0.21	6	1.79 ± 0.24	0.001
Tension time index (mmHg sec/min)	2200	22	2402 ± 146.1	4	2502 ± 247.8	NS
Mean systolic ejection rate (ml/sec m^2)	13,000	28	$10,870 \pm 582.8$	7	6545 ± 520	0.001

agreement with an increase of systemic vascular resistance in cardiogenic shock.

In the presence of cardiogenic shock, the mean pulmonary artery pressure was increased to a mean value of 31 ± 2 mmHg, whereas in the non-shock state only a slight increase (23 ± 1 mmHg) was found ($P < 0.02$) (Tables 1 and 2). In both groups the pulmonary vascular resistance was within normal limits. End-diastolic pressure in the right ventricle was 11 ± 0.9 mmHg higher in patients with cardiogenic shock than in patients with uncomplicated myocardial infarction (7 ± 0.7 mmHg; $P < 0.05$); however, there was a considerable degree of overlapping. Compared with healthy persons, the stroke work index of the right ventricle was high (11.2 ± 0.8 g m/m^2) because of the increase in pulmonary artery pressure after the beginning of myocardial infarction. In contrast to patients with cardiogenic shock, the right ventricular stroke work index was significantly diminished ($P < 0.1$). In cardiogenic shock right ventricular outflow resistance was twice raised (0.218 ± 0.03 mmHg sec/ml) compared to patients without shock (0.130 ± 0.01 mmHg sec/ml; $P < 0.05$). The difference in arteriovenous oxygen tension was, as is to be expected from the much reduced cardiac output ($41 \pm 2.5\%$), significantly higher ($P < 0.001$) when shock had developed than in patients without shock ($30 \pm 1.3\%$). As left ventricular stroke work index decreased depending on severity of the myocardial infarction, and at the same time the filling pressure of the left ventricle

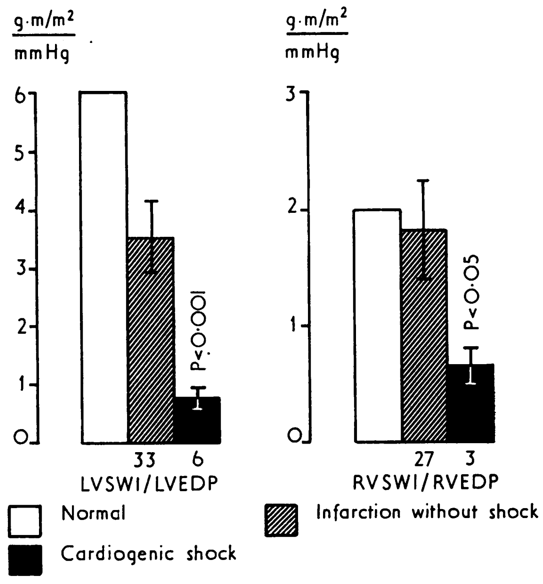

FIG. 1 *LVSWI/LVEDP and RVSWI/RVEDP in cardiogenic shock and in uncomplicated myocardial infarction.*

increased, the quotient of stroke work index and end-diastolic pressure of the left ventricle was examined and compared with the corresponding quotient for the right ventricle in both groups. As is shown in Fig. 1, there were considerable differences between the right and left ventricle. Compared with healthy persons the quotient left ventricular stroke work index (LVSWI)/left ventricular end-diastolic pressure (LVEDP) was, in patients with myocardial infarction and not suffering from cardiogenic shock, lowered to 3.5 ± 0.3 g m/m^2 mmHg. This value decreased further, in patients with cardiogenic shock, to 0.74 ± 0.1 g m/m^2 ($P < 0.001$). In contrast, in the non-shock state right ventricular stroke work index (RVSWI)/right ventricular end-diastolic pressure (RVEDP) was 1.89 ± 0.2 g m/m^2 mmHg not significantly lower than in healthy persons and only in cases of cardiogenic shock did it show a significant ($P < 0.05$) decline to 0.68 ± 0.1 g m/m^2 mmHg.

According to Krayenbühl (1969), the quotient of mean ejection rate and left ventricular end-diastolic pressure (LVEDP) is a reliable measure of the contractile state of the left ventricle provided that the afterload is identical in both groups. As can be seen from Table 1, mean arterial pressure was not significantly different in the non-shock state from that of cardiogenic shock. Vasopressor drugs, immediately initiated after diagnosis of cardiogenic shock was made (see definitions), might be responsible for the normal arterial pressure. Maximal systolic arterial cuff pressure in the patients with cardiogenic shock was 90 mmHg on admission; mean systolic arterial pressure was increased by vasopressor therapy at the time of haemodynamic measurement to 119 mmHg. The values of mean systolic ejection rate and left ventricular end-diastolic pressure are shown in Fig. 2. Though there is overlapping in both groups the mean value in cardiogenic shock was 250 ± 25 ml/sec m^2 mmHg, less than one-third of that for patients without shock (844 ± 86 ml/sec m^2 mmHg; $P < 0.001$). Only 6·7 per cent without cardiogenic shock had a quotient of less than 330 ml/sec m^2 mmHg.

Fig. 3 shows that the cardiac index was decreased with raised filling pressure of the left ventricle. Neither left ventricular end-diastolic pressure nor cardiac index is sufficient to give a clear clinical picture, since cases with only slight diminished cardiac output and a high increase in left ventricular end-diastolic pressure were seen, and vice versa. The interaction of left ventricular end-diastolic pressure and cardiac output is, however, an excellent indicator of the prognosis in acute myocardial infarction, because 6 of the 9 patients (67%) with a filling pressure exceeding 17 mmHg and a cardiac index less than 1·8 l./min per m^2 did not survive.

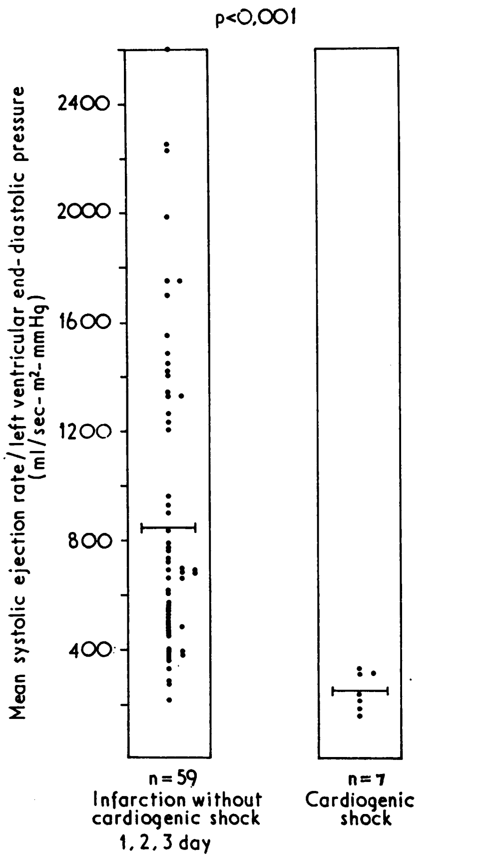

FIG. 2 *Contractile state of the heart after myocardial infarction, as estimated from the relation of mean systolic ejection rate to left ventricular end-diastolic pressure.*

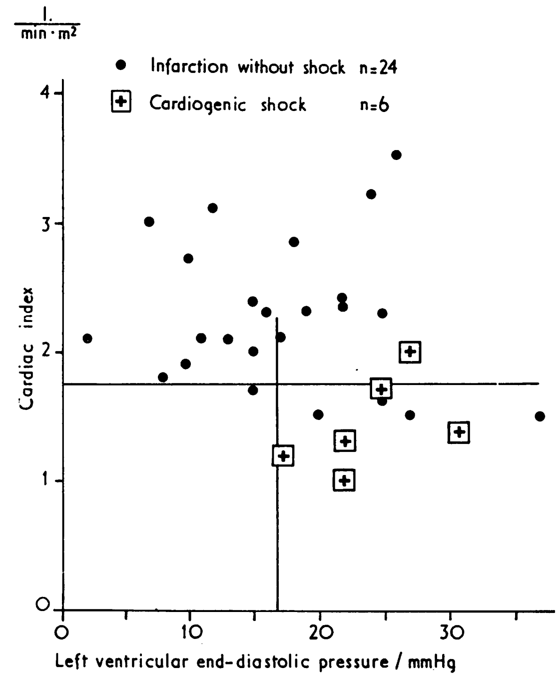

FIG. 3 *Relation of cardiac index to filling pressure in the left ventricle. Note that about 70 per cent of patients with a left ventricular end-diastolic pressure over 17 mmHg and a cardiac index below 1·8 l./min m² died. The patient far on the right died some weeks after myocardial infarction following progressive heart failure.*

In 35 patients an index related to the immediate prognosis and the early recognition of impending cardiogenic shock was derived from the haemodynamic results as follows:

$$\frac{(LVSP - LVEDP) \cdot CI}{LVEDP \cdot AVDO^2}$$

(p. 824) was investigated. Twelve non-survivors (6 with cardiogenic shock) were compared with 23 survivors (Fig. 4). The mean value in the first group was 0·18, significantly ($P < 0·05$) smaller than in the rest of the patients with acute myocardial infarction (0·5). No patients with myocardial initial cardiogenic shock had an index higher than 0·3. Thus, including the cases with cardiogenic shock, an index below 0·3 was associated with a 78 per cent mortality.

Discussion

The classical concept of acute myocardial infarction complicated by shock has been that of a greatly reduced cardiac output with raised peripheral vascular resistance (Malmcrona and Varnauskas, 1964; Thomas, Malmcrona, and Shillingford, 1965). Recent experiences, however, indicated that stroke volume and peripheral vascular resistance alone are not sufficient to explain the haemodynamic changes in acute myocardial infarction (Bleifeld *et al.*, 1972; Rackley and Russell, 1972; Ratshin, Rackley, and Russell, 1972). Peripheral vascular resistance in our patients ranged from 673 to 3243 dyn sec cm^{-5}. Similarly, great differences in individual values are reported from other authors (Rackley and Russell, 1972; Cohn and Luria, 1966; Freis *et al.*, 1952; Gilbert, Aldrich, and Anderson, 1951; Gunnar *et al.*, 1966). The same is true for the stroke volume. It is necessary, therefore, to take other haemodynamic parameters into consideration.

The functional state of the heart is complex and may be altered by different factors such as the preload which is expressed by the pressure and the

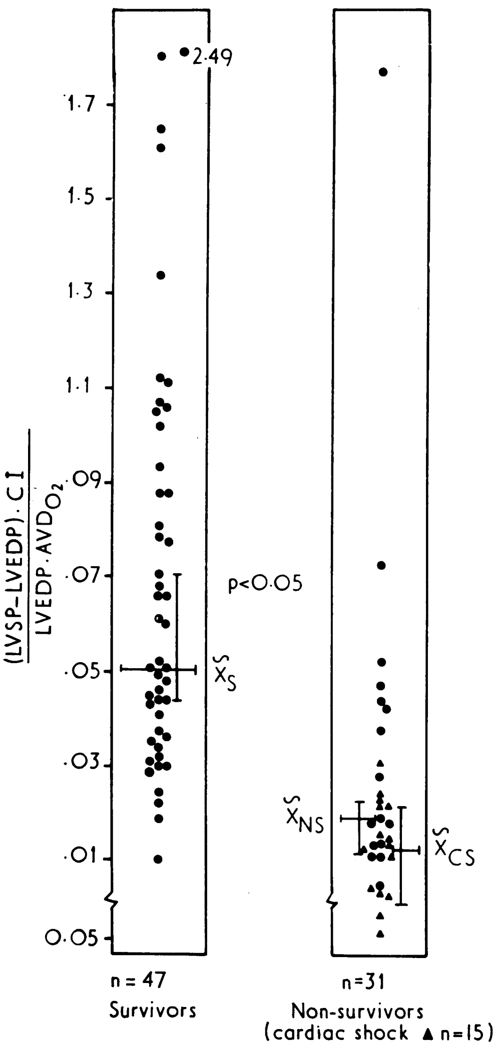

FIG. 4 *Prognostic value of an index from* $\frac{(LVSP-LVEDP)\cdot CI}{LVEDP\cdot AVDO_2}$ *in patients with cardiogenic shock compared to the non-shock state.* $\tilde{X}_S$, *median value survivors;* $\tilde{X}_{NS}$, *median value non-survivors;* $\tilde{X}_{CS}$, *median value cardiogenic shock.*

volume at the end of the diastolic time, the afterload which is equivalent to the intramyocardial tension developed, the contractile state of the myocardium, the acceleration of contraction, and the compliance. Examining some of these factors, the haemodynamic function of the heart in acute myocardial infarction was investigated in two groups of patients, without cardiogenic shock and with cardiogenic shock as defined primarily by clinical signs.

Though, particularly in the group without cardiogenic shock, the haemodynamic function and the clinical spectrum ranged from moderate insufficiency of the heart to nearly normal, the haemodynamic function of the left ventricle was, on the average in the initial phase, always impaired when compared with values for healthy persons. This could be seen from the decrease in cardiac output, stroke volume, stroke work of the left ventricle, cardiac minute work, and mean systolic ejection rate as well as from an increase in left ventricular filling pressure (Table 2).

The serial investigation in the initial phase after acute myocardial infarction – in the present study the first three days – in patients without cardiogenic shock exhibited no significant haemodynamic changes.

As the necrosis in myocardial infarction is usually in the left ventricle (Saphir *et al.*, 1935; Wartman and Hellerstein, 1948), deterioration of left ventricular function is the main problem. In cardiogenic shock, the performance of the left heart is most impaired. A high end-diastolic pressure, a low stroke volume, and, in some cases, a low cardiac output in spite of moderate acceleration of heart rate are characteristic of this clinical syndrome (Bleifeld *et al.*, 1972; Rackley and Russell, 1972, and Ratshin *et al.*, 1972). In the same way left ventricular stroke work index and mean systolic ejection rate, because of the decrease of outflow velocity, are diminished independently of the severity of myocardial infarction. The impairment of contractility was judged by the decrease in the ratio of mean systolic ejection rate to left ventricular end-diastolic pressure, and this showed the most impressive reduction in cardiogenic shock: the estimation of contractility using this quotient is justified in this investigation, in spite of the dependence of mean systolic ejection rate on the afterload, because there were no significant differences in the mean arterial pressure of the patients with and those without cardiogenic shock (Table 1). This was partly because of the application of vasopressors. It has been argued that application of vasopressors might extend the size of the infarction and by this means influence the course of seriously ill patients (Maroko *et al.*, 1971). However, an adequate coronary artery perfusion pressure is a major determinant for the contractile state of the myocardium and accordingly for the function of the heart as a pump (Arnold *et al.*, 1968). Decrease of mean arterial pressure below 70 to 80 mmHg has been found to be followed by a decrease of cardiac output and an increase in left ventricular filling pressure (Sugimoto *et al.*, 1968). Thus, irrespective of the potential hazards, especially of increasing myocardial oxygen consumption, the application of

TABLE 3 *Comparison of various haemodynamic parameters in anterior and inferior infarction.*

Localization	*Central venous pressure (mmHg)*	*Mean pulmonary capillary pressure (mmHg)*	*Pulmonary end-diastolic arterial pressure (mmHg)*	*Left ventricular end-diastolic pressure (mmHg)*
Anterior wall n=16	7·1±4·8	16·8±8·7	17·8±7·8	17·6±6·6
	NS	NS	NS	NS
Inferior wall n=18	7·7±4·0	14·2±7·3	15·8±6·2	16·8±7·7

vasopressor drugs seems reasonable for the increase of arterial pressure in severe power failure, if it is below 50 mmHg (Harrison, 1973).

With the impairment of contractility, the heart in cardiogenic shock is only able to deliver a small stroke volume. Because of the high peripheral vascular resistance in most cases mean arterial pressure was normal and the outflow impedance to the left ventricle was significantly increased.

It has been supposed that the site of infarction would be of major importance for the development of left or right heart failure. In this context inferior infarction has been assumed to be accompanied more often by right ventricular failure than by anterior infarction (Russel *et al.*, 1970). However, as can be seen from Table 3, in the group under study no significant differences in the mean values of central venous pressure, mean pulmonary capillary pressure, end-diastolic pulmonary artery, and left ventricular end-diastolic pressure in anterior and inferior wall infarction could be seen. The correlation between central venous pressure and pulmonary capillary pressure in the 34 patients was, with r=0·61 in anterior myocardial infarction, not significantly different from that in inferior infarction (r=0·68). Similar results were obtained when central venous and left ventricular end-diastolic pressure were correlated for anterior (r=0·70) and inferior infarction (r=0·50) (Fig. 5). In 2 of 18 measurements in inferior infarction and in 2 out of 16 measurements right ventricular end-diastolic pressure was raised to a maximum of 7 and 11 mmHg in the presence of a normal left ventricular filling pressure (Fig. 5). There are two possible explanations for this disparity in the behaviour of the filling pressures in the left and right ventricle. First, the infarction could involve the right ventricle more than the left ventricle. However, in the study of Harnarayan *et al.* (1970) only 4 of 20 patients (20%), who died from cardiogenic shock in acute myocardial infarction, had a larger necrosis in the right than in the left ventricle. As 10 to 20 per cent of patients with infarctions developed cardiogenic shock (which was exclusively studied in this paper) in only 2 to 4 per cent of all those with infarctions would the disparity in filling pressures account for the larger extent of the necrosis in the right than in the left ventricle. The second explanation concerns the alterations of the compliance of the ventricular wall after myocardial infarction; recent studies from our laboratory (Bleifeld *et al.*, 1973) have shown that left ventricular stiffness is increased on the first day after infarction and is followed by a qualitatively similar increase in right ventricular stiffness. This increase in the stiffness of the right ventricle, especially in infarction with

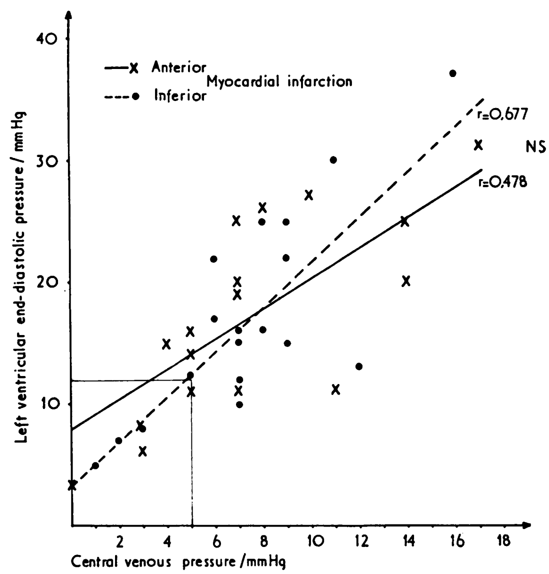

FIG. 5 *Relation of left ventricular end-diastolic pressure and central venous pressure. Note that there is no statistical significance between the regression lines in anterior (——) and inferior (- - -) myocardial infarction. The lines in the lower left edge indicate upper normal values.*

septal involvement, might be the reason for the rare cases with increased right ventricular filling pressure and possibly right heart failure in the presence of normal left ventricular end-diastolic pressure. Thus, with the exception of very few cases, the site of infarction exerted no significant influence on the occurrence of right heart failure.

From these results it is obvious that in myocardial infarction the effect on the haemodynamic function of the left ventricle is fundamentally different from that on the function of the right ventricle. While the immediate consequences of myocardial infarction are the decrease in stroke work and contractility of the left ventricle, right ventricular function is only secondarily affected. Following the increase in left ventricular end-diastolic pressure, the reduction of stroke volume, the rise in pulmonary wedge pressure and, accordingly, mean pulmonary artery pressure rise, the afterload to the right ventricle was increased. Consequently, the outflow impedance to the right ventricle was greatly increased. Right ventricular end-diastolic pressure and stroke work were increased compared to normal, mainly because of the changes in the loading conditions to the right heart. When the stroke volume was decreased in cardiogenic shock, the stroke work of the right ventricle was accordingly reduced to values below normal.

Plots of the cardiac filling pressure and stroke work index filling pressure relation are useful in estimating the function of the left and right ventricle in acute myocardial infarction.

In Fig. 6 and 7 cardiac output and stroke work index of both chambers are correlated with the filling pressures of the respective ventricle. Compared to normal values, the mean values of end-diastolic pressures and cardiac output (Fig. 6) in acute myocardial infarction shift downward and to the right, thus indicating the deterioration of function in both ventricles. If we regard the relation between end-diastolic pressures and stroke work index of both ventricles (Fig. 7), which is dependent on the afterload as well as on the stroke volume, the plots of the mean left ventricular stroke work index-left ventricular end-diastolic pressure again move downward and to the right in infarction without shock and even more in cardiogenic shock. In contrast, mean right ventricular stroke work index-left ventricular end-diastolic pressure shifts upwards and right in the infarction not complicated by cardiogenic shock, indicating that right ventricular function evaluated from stroke work index and filling pressure is not essentially altered from that of a heart without myocardial infarction. However, a shift of the plot right ventricular stroke work index against right ventricular end-diastolic pressure to the right and slightly downward is observed in cardiogenic shock. This movement is mainly due to the extreme decrease in stroke volume following the impairment of left ventricular function in acute myocardial infarction, whereas mean pulmonary artery pressure is increased. If the stroke volume were normal, the stroke work of the right ventricle would be increased in cardiogenic shock. From these considerations it can be derived that right ventricular function is only secondarily affected in myocardial infarction. This is in agreement with a recent study of Crexells *et al.* (1972) that patients with depressed left ventricular function also tended to have depressed right ventricular function.

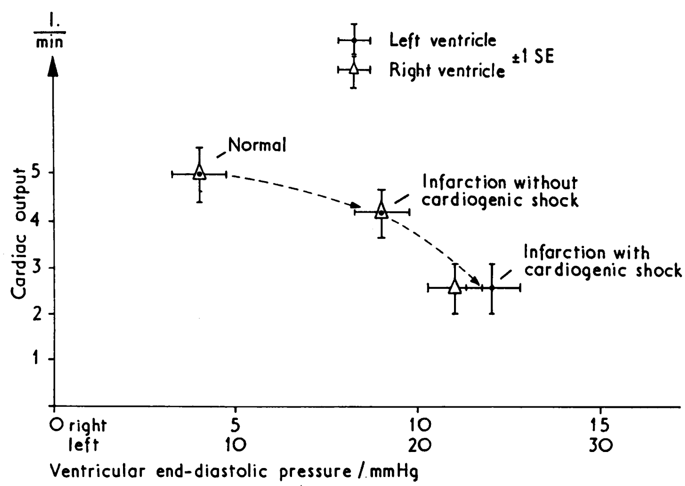

FIG. 6 *Relation of cardiac output to filling pressures in myocardial infarction without and with cardiogenic shock on the basis of data presented in this report (see text).*

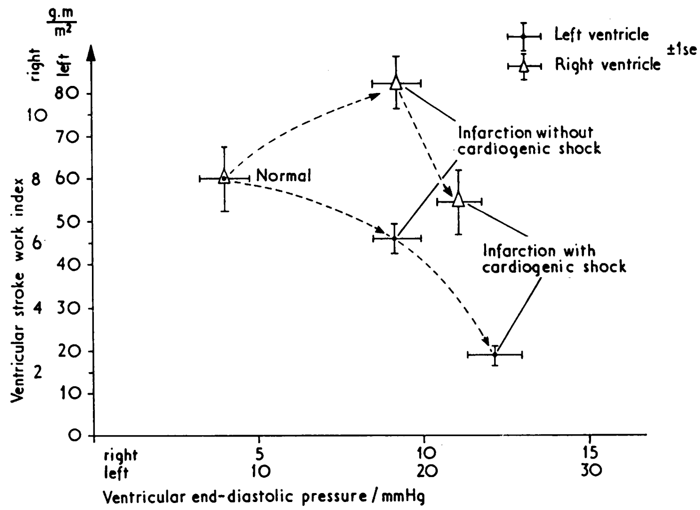

FIG. 7 *Relation of stroke work index to the end-diastolic pressures of the considered ventricle. Note that right ventricular stroke work is increased compared to normal in uncomplicated infarction, and decreases if stroke volume diminishes after cardiogenic shock. In contrast, left ventricular stroke work index decreases uniformly after myocardial infarction.*

Following this concept, attention in acute myocardial infarction has mainly to be directed to the function of the left ventricle which is extremely reduced in cardiogenic shock. However, the different parameters assessed in both groups showed a considerable overlap. No single parameter was sufficient to characterize the functional state of the left ventricle. For early identification of patients in cardiogenic shock and those threatened by cardiogenic shock, the combined evaluation of different haemodynamic parameters is necessary. One of the possibilities is to assess myocardial performance by relating cardiac output, stroke work index, or cardiac minute work to left ventricular end-diastolic pressure. Among the patients with a raised filling pressure above 17 mmHg and a reduced cardiac index below 1·75 l./min per m², most had an immediate poor prognosis and about 70 per cent died despite conventional medical treatment. The group with cardiogenic shock is further characterized by a low value of left ventricular stroke work index/left ventricular end-diastolic pressure. When this quotient was less than 1·2, mortality increased to 80 per cent. The prognostic course may well be judged from a new prognostic index including left ventricular systolic pressure, end-diastolic pressure, cardiac index and arteriovenous oxygen difference, which are characteristically altered in cardiogenic shock. This index seems to be a good diagnostic guide, because the overlap between the non-shock state and patients who have cardiogenic shock after myocardial infarction was very low. Patients with a prognostic index below 0·3 had a poor prognosis and a mortality of 78 per cent. The practical value of this index can be seen from the fact that the parameters used in the index can be measured without entering the left ventricle. In the absence of aortic stenosis, systolic arterial pressure is equal to left ventricular systolic pressure. Left ventricular end-diastolic pressure is identical to pulmonary end-diastolic pressure, deviating only ± 3 mmHg ($P < 0{\cdot}05$) (Merx *et al.*, 1973). Accordingly the index can be changed to

$$\frac{(\text{Systolic arterial} - \text{pulmonary end-diastolic pressure}) \cdot \text{cardiac index.}}{\text{pulmonary end-diastolic presure} \cdot \text{arteriovenous oxygen difference}}$$

In conclusion then, haemodynamic measurements of right and left ventricular function in the early phase of acute myocardial infarction resulted in information from which patients with a poor prognosis can be recognized early from those with a good outcome. Certainly extensive invasive investigations are indicated only if the individual patient is in cardiogenic shock or in severe left heart failure. The haemodynamic measurement of cardiac function in this group is of particular value for the kind of therapy, especially the initiation of circulatory assist and emergency cardiac operation.

Recent experiences have shown that circulatory assist devices may reduce the extremely high mortality rate (85–100%; Kuhn, 1967; Swan *et al.*, 1970) especially when combined with myocardial revascularization. Scheidt *et al.* (1973) reported an initial survival rate of 40 per cent (35 of 87 patients) using intra-aortic balloon pulsation in cardiogenic shock and 15 patients (17%) left the hospital. In the study of Dunkman *et al.* (1972) 25 per cent of patients with cardiogenic shock survived with intra-aortic balloon pulsation alone, another 15 per cent survived after additional emergency coronary bypass operation. Butner *et al.* (1969) reported the discharge of 9 of 29 patients (31%) treated with intra-aortic balloon pulsation for cardiogenic shock after myocardial infarction. Though clinical experience with circulatory assist and emergency coronary surgery are still limited the ineffectiveness of pharmacological treatment suggests that these techniques may help to reduce the mortality rate of cardiogenic shock.

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